N91-20648

IMPACT OF INERTIA, FRICTION AND BACKLASH UPON FORCE CONTROL IN TELEMANIPULATION

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ABSTRACT

The mechanical behavior of master controllers of telemanipulators has been a major concern of both designers and implementors of telerobotic systems. In general, the literature recommends that we construct telemanipulator systems that minimize inertia, friction, and backlash in an effort to improve telemanipulative performance. For the most part, these recommendations are founded upon theoretical analysis or simply intuition. Although we do not challenge the recommendations on their merit, we were interested in measuring the material consequences of building and fielding telemanipulators that possess less than ideal mechanical behaviors. Experiments are described in this paper in which forces in a mechanical system with human input are evaluated as a function of mechanical characteristics such as inertia, friction and backlash. Results indicate that the ability of the human to maintain gripping forces was relatively unaffected by dynamic characteristics in the range studied, suggesting that telemanipulator design in this range should be based on task-level force control requirements rather than human factors.

INTRODUCTION

Designers of telerobotic systems are often faced with important trade-offs concerning the mechanical characteristics of the manipulator mechanisms and their impact upon the performance capability of the human operator. For example, a designer can use direct-drive actuators to substantially reduce backlash and friction, but to do so requires the use of larger actuators with greater inertial characteristics. Smaller geared-drives can be used but not without encountering higher levels of backlash and friction. It is possible to reduce backlash in geared drives, but not without increasing friction to some degree. Finally, most designers would prefer to minimize or compensate for friction in telemanipulators, caused by gearing, cables, etc. Unfortunately, friction is both difficult to eliminate and difficult to model and predict accurately, making friction compensation in control systems difficult even though complex compensation algorithms can be implemented in computer software.

Knowing the relative consequences and interrelationships among mechanical properties of telemanipulators, in terms of human controller performance, provides:

a) opportunities for confident and strategic selection of telemanipulator system components with tolerable levels of inertia friction, and backlash; and

b) greater opportunity for diversity and competition among master-slave controller designs (e.g.,degrees-of-freedom, actuators, etc.).

A dominant performance requirement for effective telemanipulation is timely and accurate operator detection and control of remote grasp forces. This is a particular problem when teleoperating manipulators in remote environs where the opportunities for unexpected disturbances in remote grasp are high. Disturbances in grasp can result from sudden forces applied by the object within the gripper, or by the manipulator, which result in rapid movement and/or changes in the forces between the object and the manipulator. The net effect can be either complete loss of contact with the object, or object slippage and realignment within the gripper. This certainly lengthens the job if the operator must regrasp and reorient either the object or the manipulator arm. Thus, high-performance, or at least operationally acceptable, manipulation

depends on the interrelationships between quality of force feedback information and manipulator dynamics.

The objective of this study was to determine whether realistic variations in inertia, friction, and backlash or deadspace, produced material challenges to the human operator's capacity to control grasp force in the face of an unexpected disturbance.

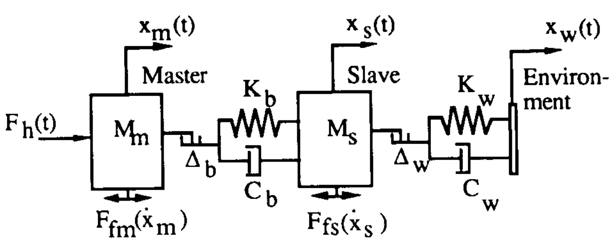
METHODS AND MATERIALS

Subjects

Eight males and one female ranging in age from 20 to 36 years participated in the experiment. All subjects reported and appeared to be in good health with no history of neuromuscular disorders. Participation in the experiment was on an informed consent, voluntary, and paid basis.

Apparatus

A mechanical system model of a one degree-of-freedom, bilateral, master/slave system with the slave in contact with the work environment is shown in Figure 1.



Nomenclature:

M_m, M_s : Inertia of the master and slave

K_b, C_b: Stiffness and damping in the master/slave system

Δ_b, Δ_w: Backlash in the master/slave system and work environment

K_w, C_w: Stiffness and damping between the slave manipulator and the work environment

$F_h(t)$: Force applied by the human

x_m, x_s, x_w: Position of the master, slave and work environment, respectively

F_{fm}, F_{fs}: Friction force on master and slave, respectively

Figure 1: Master/slave system model

The model is non-linear due to the incorporation of friction and backlash. In an actual master/slave system with a number of power transmitting components there will be a series of masses and associated backlashes. However, these can generally be lumped into equivalent masses, backlash, etc. [1]. Friction can take various forms such as dry, fluid, etc., and is always a resistive force that is dissipative and has a retarding effect on the motion of the system [2].

For the purposes of our experiment, the bilateral system described in Figure 1 was simplified to that shown in Figure 2. The simplified system model can represent a case in which the interface between the slave device and the work environment (the object being manipulated) is relatively rigid (K_w is large and Δ_w is small) and the master/slave system is relatively compliant, or a case in which the interface between the slave device and the work environment is relatively compliant and the master/slave system is relatively rigid (K_b and C_b are large, and Δ_b is small). In the former case, the slave device can be considered to be coupled rigidly to the environment, with dynamic characteristics lumped between the master and slave. In the latter case, the master can be considered to be coupled rigidly to the slave, with dynamic characteristics lumped between the slave and the work environment. In all cases, the force applied by the human in the simplified model, $F_h(t)$, corresponds to the force applied by the human to the master device in Figure 1.

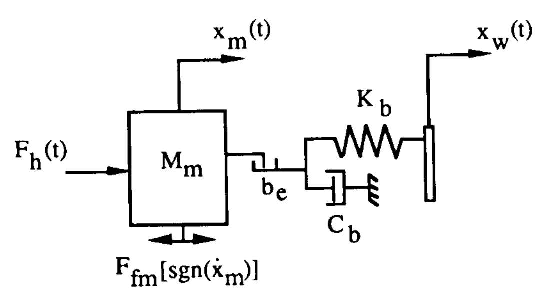


Figure 2. Simplified system model implemented in experiments

The apparatus system used in the experiments employed direct drive actuators, and hence had no intrinsic backlash [3]. Mechanical friction was also minimized in the system by using brushless motors and a precision linear slide. The system used was nearly an ideal, linear second-order system with a maximum positioning natural frequency of 30 Hz.

A strain gauge force sensor was used to measure forces exerted by the subjects. A high-resolution encoder was employed for position feedback and velocity estimation. A microcomputer controlled the position of the actuator and recorded: a) position commands; b) actual position; c) strain-gauge voltages; and d) computer clock time. A schematic of the experimental configuration is shown in Figure 3.

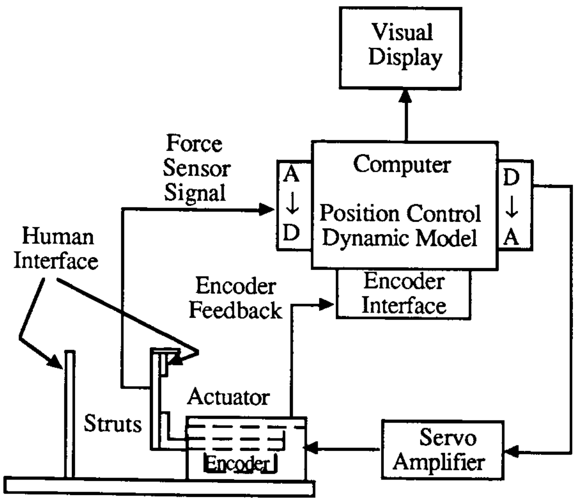


Figure 3. Experimental apparatus

Stiffness, damping, inertia, friction and backlash characteristics perceived by the human subject were programmed and controlled by system software. Apparent backlash was implemented by providing a dead band between commanded position and the actual position. Apparent friction was produced using an algorithm with velocity of the mass and the forces on the mass as inputs. Impedance control techniques were employed for implementing the desired stiffness, damping and mass parameters [4].

Procedures

Following an initial period of practice with the task, subjects were asked to grasp the struts on the apparatus (one fixed and one connected to the actuator) with the thumb and index finger. The subjects were instructed to squeeze, using a pulp-pinch grasp, until they achieved a 5 N force. The level of force was indicated by movement of a computer screen cursor to a visual target. The subjects held the force until they were confident that they could recognize and return to the 5 N force if a sudden loss of force was experienced

Following the subject's signal to begin, the computer would move the position of the apparent work environment, $x_w(t)$, 6 mm in the direction away from the subject's index finger. This step-displacement, which was produced at a random interval between 2 and 7 s after the subject signalled the start of the trial, decreased the force acting against the subject's finger. The subject's goal was to maintain a constant 5 N force at all times regardless of a positional disturbance. The computer began to record at a 166.7 Hz rate at 2 s before the 6 mm step occurred and recorded for another 6 seconds following the step.

Experimental Design and Analysis

To simplify the experiment, the stiffness and damping parameters were held constant (K = 3.7186 N/mm, C = 0.10677 N-s/mm). Earlier testing showed that variations in these parameters did not have a material affect upon grasp force control within the limits of the independent variables studied in this experiment. Static frcition was equal to dynamic (coulomb) friction in the tests. Each subject repeated a trial 5 times under each of 27 combinations of three-levels of

Table I: System configurations used in experiments

Config. Number	Mass (Kg)	Friction (Newtons)	Backlash (mm)	Nat. Freq (hz)	Damping Ratio
1	0.6813	0.0	0.00	11.76	1.06
2	0.6813	0.0	0.25	11.76	1.06
3	0.6813	0.0	0.50	11.76	1.06
4	0.6813	1.5	0.00	11.76	1.06
5	0.6813	1.5	0.25	11.76	1.06
6	0.6813	1.5	0.50	11.76	1.06
7	0.6813	3.0	0.00	11.76	1.06
8	0.6813	3.0	0.25	11.76	1.06
9	0.6813	3.0	0.50	11.76	1.06
10	1.3626	0.0	0.00	8.31	0.75
11	1.3626	0.0	0.25	8.31	0.75
12	1.3626	0.0	0.50	8.31	0.75
13	1.3626	1.5	0.00	8.31	0.75
14	1.3626	1.5	0.25	8.31	0.75
15	1.3626	1.5	0.50	8.31	0.75
16	1.3626	3.0	0.00	8.31	0.75
17	1.3626	3.0	0.25	8.31	0.75
18	1.3626	3.0	0.50	8.31	0.75
19	2.7252	0.0	0.00	5.88	0.53
20	2.7252	0.0	0.25	5.88	0.53
21	2.7252	0.0	0.50	5.88	0.53
22	2.7252	1.5	0.00	5.88	0.53
23	2.7252	1.5	0.25	5.88	0.53
24	2.7252	1.5	0.50	5.88	0.53
25	2.7252	3.0	0.00	5.88	0.53
26	2.7252	3.0	0.25	5.88	0.53
27	2.7252	3.0	0.50	5.88	0.53

backlash, friction, and inertia shown in Table I. Each subject experienced all combinations of the experimental conditions in a random order.

The mean grasp force time history following the step disturbance of 5 trials served as the performance metric under each of the test conditions. Grasp control performance was characterized using each of the following metrics:

a) magnitude of force loss following the step disturbance;

b) time needed by the subject to return to 4.5 N or 90 percent of the initial grasp force (referred to as force recovery period); and

c) magnitude of grasp force following grasp recovery (mean force recorded during the last 2 s of the trial).

The above metrics were examined using randomized-block ANOVA to determine whether or not inertia, friction, backlash, or any two and three-way interactions were significant. All tests were conducted fixing Type I and Type II errors at p=0.05 and p=0.10 respectively.

RESULTS

Magnitude of Force Loss

As the apparent work environment stepped away from the grasp of the subject, pinch grasp force declined. The ideal response would show no change in force level or zero force loss.

As shown in Figure 4, the average magnitude of this decline was largely unaffected by the different combinations of mass, friction, and backlash experienced. Increasing the level of backlash did produce only slightly greater losses in force ($F = 8.13$; $df = 2,16$; $p = 0.0037$); however, as shown in the figure the effect was not material in nature. All remaining effects, as well as their interactions, were not statistically significant ($p \geq .05$; Power $\geq .90$).

Time Period Needed for Recovery of Grasp Force

The period of time needed for the subject to recover 90 percent of the original grasp force following the step should be kept as small as possible. The analyses indicated that following the step disturbance, recovery times were essentially the same regardless of inertial, friction, and backlash characteristics examined.

Magnitude of Grasp Force Following Grasp Recovery

Ideally, the subject should recover from the loss of force following the disturbance, and return grasp force back to the initial levels. The ANOVA results revealed that differences in mass, friction, and backlash had no effect upon the level of force established following recovery from the disturbance. However, subjects almost always produced greater than 5 N of grasp force upon reestablishing their perceived grasp force goal.

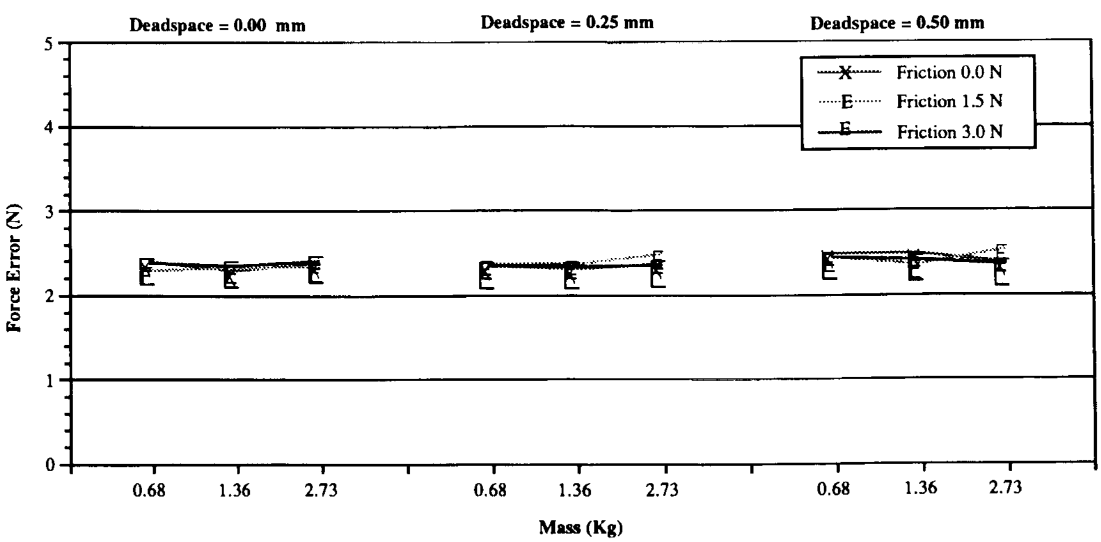


Figure 4. Magnitude of force loss

Interrelationships Among Force Error, Force Recovery Period, and Shift in Force Baseline.

The Pearson-product moment correlations showed no meaningful relationships existed between measures of subject force control performance and variations in levels of mass, friction, or backlash.

DISCUSSION

Plots of force time histories, such as those in Figure 5, showed that subjects began to actively recover control of force after about 140 ms, and that their restoration behavior was similar to an over-damped second-order force response with a dominant time constant of approximately 280 ms. During the initial 140 ms following the step, the grasp force does not fall to zero.

The hand is actively controlling forces prior to the step. As the actuator moves away from the finger, the active tension set of the extrinsic and intrinsic musculature of the hand is impeded only by the actuator. Thus, the finger initially "follows" the movement, continuing to apply more than half of the original 5 N.

Once the loss of force is detected, the subject actively contracts affected muscles to return to a pre-step level of tension. The rate of return, or force recovery period, is largely instruction-dependent. The rate we observed was established by the subject's need to restore force as quickly and as accurately as possible without overforcing. Thus, the subject attempted to produce a controlled over-damped response without overshooting the perceived level or muscle tension needed to regain the desired grasp force. Had the subjects been instructed to recover grasp force as quickly as possible without concern about overforcing, they would have produced much shorter force recovery periods, would have overshot the grasp force goal, and then reduced grasp force to the perceived goal. In this experiment, the subjects tended to return to stable force levels that were slightly greater than the original 5 N.

Deadspace was experienced during the initial motion of the actuator. This space was traversed passively by the finger as it "followed" the displaced actuator. The finger had preloaded the actuator again prior to the initiation of active force control by the finger. Once the finger had passed through the deadspace, backlash no longer existed. This left the subject facing only mass and friction effects when returning forces to initial levels.

Static and dynamic friction forces, from the perceptual perspective of the subject, appear to be lumped with the inertial or mass effects. Thus, the operator perceives the force, whether due to inertial or friction effects, as an equivalent cue.

The plots in Figure 5 also reveal that the human subjects applied restoring forces in a very consistent manner even though the apparent reaction force was a result of different combinations of forces (friction, inertial, spring and damper). This suggests that the human subjects may treat all reaction forces similarly. However, as can be seen in Figure 6, there are differences in the work environment force response for various combinations of dynamic characteristics. These are due the mechanical properties, and the differences appear to be independent of human input.

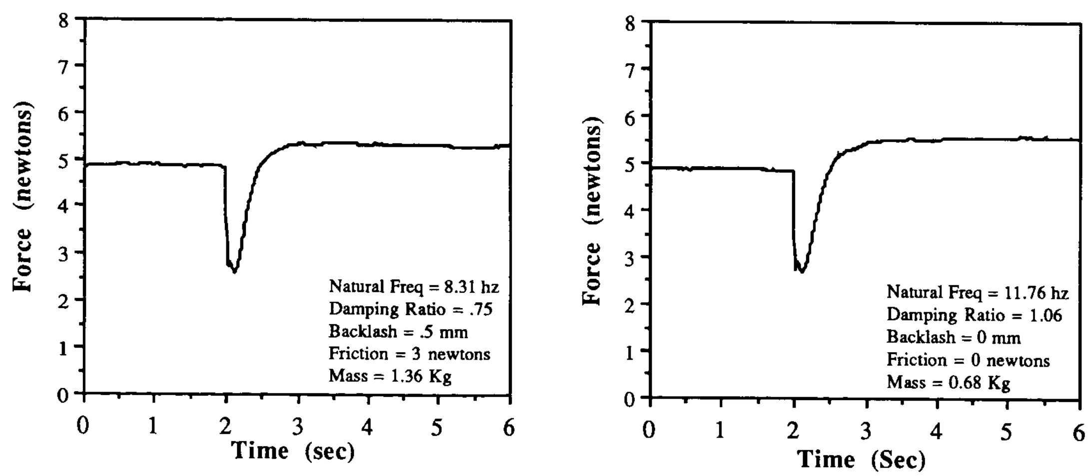
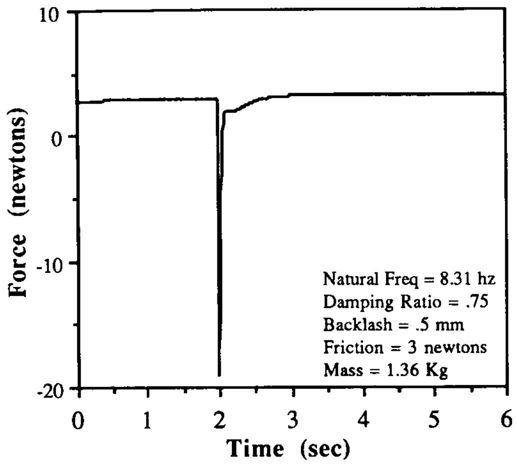


Figure 5. History of force applied by human subject



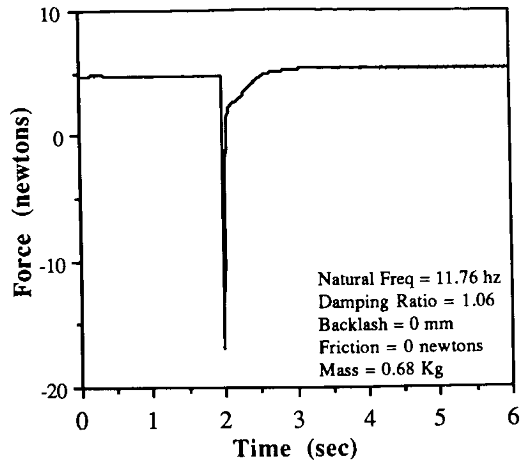


Figure 6. History of work environment force

CONCLUSIONS

From our findings it appears the operator perceives forces, whether due to inertial or friction effects, as equivalent cues. This indicates that master/slave manipulator dynamics may be more important than human force control characteristics in high-performance telemanipulation in the force domain. It appears that the human operator is tolerant of reasonable levels of master-controller mass, friction, and backlash characteristics when compelled to maintain grasp forces within desired operating ranges. It is not clear whether these conclusions would hold for higher levels of mass, friction, or backlash that those addressed in our experiment. Preliminary studies indicate that if there is a significant difference between the static and dynamic coefficients of friction, then acceptable force control performance becomes more difficult to achieve.

ACKNOWLEDGMENTS

This work was supported by the Wisconsin Center for Space Automation and Robotics in part by NASA under grant NAG-W975 and by a consortium of industrial sponsors.

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